

Observational Constraints on the Role of the Crust in the Post-glitch Relaxation

M. Jahan-Miri

Department of Physics, Shiraz University, Shiraz 71454, Iran
 jahan@physics.susc.ac.ir

ABSTRACT

The observed large rates of spinning down after glitches in some radio pulsars have been previously explained in terms of a long-term spin-up behavior of a superfluid part of the crust of neutron stars. We argue that the suggested mechanism is not viable; being inconsistent with the basic requirements for a superfluid spin-up, in addition to its quantitative disagreement with the data. Hence, the observed post-glitch relaxations may not be interpreted due only to the effects of the stellar crust.

Subject headings: stars: neutron – hydrodynamics – pulsars

1. Introduction

Glitches, and post-glitch relaxations, are widely believed to be effects caused by (the superfluid component in) the crust of neutron stars (see, eg., Lyne & Graham-Smith 1998; Krawczyk et. al. 2003). There exist, however, observational data on glitches that could not be possibly due to the role of the stellar crust. The data have been previously explained (Alpar, Pines & Cheng 1990; hereafter APC) in terms of a suggested spin-up of (a part of) the crustal superfluid by the spinning down crust (“the container”) over a time much larger than the associated relaxation timescale. However, a closer look at the relative rotation of the superfluid and its vortices reveals that the suggested mechanism fails quantitatively by, at least, more than one order of magnitude. In addition, the suggested spin-up process is also argued to be in contradiction with the well-known requirements for a superfluid spin-up. Hence, the (pinned) superfluid in the crust is not the primary cause of the post-glitch relaxation. On the other hand, the pinning of the superfluid vortices in the crust, and also in the core, of a neutron star has recently been objected by some authors on the account of the possible observations of long period precession in isolated pulsars (Jones & Anderson 2001; Link 2003; Buck-

ley, Metlitski & Zhitnitsky 2004). Thus the post-glitch relaxation must be driven by mechanism(s) other than that due only to the crust superfluidity, whether the pinning is realized or not. In section 2, the general role of an assumed superfluid component in (the crust or in the core of) a neutron star on the observable post-glitch behavior of the star is briefly described. In section 3, the relevant observational data and the problem raised by these observations against any model of post-glitch relaxation based on the effects of the crust alone are highlighted. The earlier suggested resolution (APC) of the problem is then stated. In section 4, a quantitative evaluation of the suggested mechanism is given, indicating a large disagreement with the data. The subsection 4.1 presents a more detailed discussion of the rotation of the different components in the crust, paying particular attention to the vortex lines, and arrives at the same conclusion as already deduced, in the section 4. In section 5, the feasibility of the suggested process, of spinning up of a pinned superfluid component in the crust during the spinning down of the crust itself, is questioned, altogether. The possibility of such a process is argued to be ruled out, on a general dynamical ground, and also according to the vortex creep formulation. We conclude in section 6, with a speculative suggestion for the possible

cause of the observed effect.

2. Crustal Superfluid: An Overview

The spin-down rate $\dot{\Omega}_c$ of the crust of a neutron star, with a moment of inertia I_c , obeys (Baym et al. 1969b)

$$I_c \dot{\Omega}_c = N_{\text{em}} - \sum I_i \dot{\Omega}_i \quad (1)$$

where N_{em} is the negative electromagnetic torque on the star, and $\dot{\Omega}_i$ and I_i denote the rate of change of rotation frequency and the moment of inertia of each of the separate components, respectively, which are summed over. Steady state implies $\dot{\Omega}_i = \dot{\Omega}_c = \dot{\Omega} \equiv \frac{N_{\text{em}}}{I}$, for all i , where $I = I_c + \sum I_i$ is the total moment of inertia of the star. Different models for the post-glitch recovery, and in particular the model of vortex-creep, invoke a decoupling-recoupling of a superfluid component in the *crust* of neutron stars (Alpar et al. 1984; Jones 1991a; Epstein, Link & Baym 1992). The rest of the star including the core (superfluid) is assumed in these models to be rotationally coupled to the non-superfluid constituents of the crust, on timescales much shorter than that resolved in a glitch.

The role of any superfluid component of a neutron star in its post-glitch behavior is understood as follows. Spinning down (up) of a superfluid at a given rate is associated with a corresponding rate of outward (inward) radial motion of its vortices. If vortices are subject to pinning, as is assumed for the superfluid in the crust of a neutron star, a spin-down (up) would require unpinning of the vortices. This may be achieved under the influence of a Magnus force \vec{F}_M acting on the vortices, which is given, per unit length, as

$$\vec{F}_M = -\rho_s \vec{\kappa} \times (\vec{v}_s - \vec{v}_L) \quad (2)$$

where ρ_s is the superfluid density, $\vec{\kappa}$ is the vorticity of the vortex line directed along the rotation axis (its magnitude $\kappa = \frac{h}{2m_n}$ for the neutron superfluid, where m_n is the mass of a neutron), and \vec{v}_s and \vec{v}_L are the local superfluid and vortex-line velocities. Thus, if a lag $\omega \equiv \Omega_s - \Omega_c$ exist between the rotation frequency Ω_s of the superfluid and that of the vortices (pinned and co-rotating with the crust) a radially directed Magnus force $(F_M)_r = \rho_s \kappa r \omega$ would act on the vortices, where r is the distance from the rotation axis, and $\omega > 0$

corresponds to an outward directed $(F_M)_r$, vice-versa. The crust-superfluid may therefore follow the steady-state spin-down of the star by maintaining a critical lag ω_{crit} which will enables the vortices to overcome the pinning barriers. The critical lag is accordingly defined through the balancing $(F_M)_r$ with the pinning forces.

At a glitch a sudden increase in Ω_c would result in $\omega < \omega_{\text{crit}}$, hence the superfluid becomes decoupled and could no longer follow the spinning down of the star (ie. its container). If, as is suggested, the glitch is due to a sudden outward release of some of the pinned vortices the associated decrease in Ω_s would also add to the decrease in ω , in the same regions. Therefore a fractional increase $\frac{\Delta \dot{\Omega}_c}{\dot{\Omega}_c}$ same as the fractional moment of inertia of the decoupled superfluid would be expected. This situation will however persist only till $\omega = \omega_{\text{crit}}$ is restored again (due to the spinning down of the crust) and the superfluid re-couples, as illustrated by Ω_s and Ω_c curves in Fig. 1. The vortex creep model suggests (Alpar et al 1984) further that a superfluid spin-down may be achieved even while $\omega < \omega_{\text{crit}}$, due to the creeping of the vortices via their thermally activated and/or quantum tunnelling movements. A superfluid spin-down with a steady-state value of $\omega < \omega_{\text{crit}}$, and also a post-glitch smooth gradual turn over to the complete re-coupling for each superfluid layer is thus predicted in this model. It may be however noticed that the predicted gradual (exponential) recovery of the crustal spin frequency is not an effect peculiar to the creep process. It is mainly caused due to the assumed varying amplitude of the glitch-induced jump in Ω_s in the different layers of the superfluid (corresponding to their assumed varying critical lag values), which are thus re-coupled at various times. A similar behavior should be also expected even in the absence of any creeping, given the same series of the superfluid layers. The induced $\frac{\Delta \dot{\Omega}_c}{\dot{\Omega}_c}$ during a superfluid decoupling phase according to the creep model would be indeed the same as (or slightly smaller than) otherwise.

3. Observational Constraint

The more recent glitches observed in Vela, and one in PSR 0355+54, have shown values of

$$\frac{\Delta \dot{\Omega}_c}{\dot{\Omega}_c} > 10\% \quad (3)$$

with recovery timescales ~ 0.4 d, and ~ 44 d, respectively (Lyne 1987; APC; Flanagan 1995). The data hence imply (Eq. 1) that a part of the star with a fractional moment of inertia $> 10\%$ (up to 60%) is decoupled from the crust during the observed post-glitch response. This is, however, in sharp contradiction with the above glitch models, since for the moment of inertia I_{crust} of the crustal superfluid

$$\frac{I_{\text{crust}}}{I} \lesssim 2.5\% \quad (4)$$

(APC). The disagreement with the data is indeed a fundamental shortcoming for the crustal models, and not just a quantitative mismatch. Because, the predicted increase for $\frac{\Delta\dot{\Omega}_c}{\dot{\Omega}_c}$ in these models is naturally bound to be smaller than the fractional moment of inertia of the decoupled superfluid (also see the best fit results of Alpar et al. 1993); the other possibility raised in APC, to account for the larger spin-down rates, is the point of issue in the following.

It has been suggested (APC) that the observed large values of $\frac{\Delta\dot{\Omega}_c}{\dot{\Omega}_c} \sim 20\%$ over a time scale $\tau_{\text{sp}} \sim 0.4$ d, in Vela, could be accounted for by assuming that part of the crustal superfluid *spins up*, over the *same* time period τ_{sp} (see Fig. 1a). The superfluid would thus be expected to act as a source of an additional spin-down torque on the rest of the star and could, in principle, result in $\frac{\Delta\dot{\Omega}_c}{\dot{\Omega}_c}$ values much larger than the fractional moment of inertia of the decoupled component. For this to be realized, a region of the crust-superfluid with a moment of inertia I_{sp} and a spin frequency Ω_{sp} has been assumed to support a tiny (positive) steady-state lag $\omega_{\text{sp}} \equiv \Omega_{\text{sp}} - \Omega_c \sim 3.5 \times 10^{-6}$ rad s $^{-1}$, in contrast to the much larger steady-state value of the lag $\omega \geq 10^{-2}$ rad s $^{-1}$ in the rest of the crust-superfluid. Hence, a glitch of a size $\Delta\Omega_c \sim 10^{-4}$ rad s $^{-1}$ would result in a “reversed” situation with $\Omega_c \gg \Omega_{\text{sp}}$, which is further suggested (APC) to be followed by a spinning up of the superfluid over the time period τ_{sp} , as indicated in Fig. 1a.

4. A Quantitative Check

The above spin-up scenario is however unable to account for the observed effect, quantitatively.

It assumes (APC) that the total frequency difference $(\Omega_c - \Omega_{\text{sp}})$, initially induced by the glitch, is slowly relaxed during the period τ_{sp} . In contrast, we argue that only a small fraction of the initial jump in the superfluid rotation rate might be at all preserved for any such “long-term” spin-up process. This is because the superfluid would be otherwise rotating much slower than its vortices which are, by virtue of their assumed pinning, co-rotating with the crust (see Fig. 1a). That is, the rotational lag between the superfluid and its vortices would be *much larger* than the associated critical lag. If so, the pinning could not impede the vortex motions (see above) and a fast superfluid spin-up should take place. It may be recalled that the critical lag is, by definition, the minimum lag required for the Magnus force on vortices to overcome the pinning forces. When the instantaneous lag exceeds its critical value, the pinning forces (in the azimuthal direction) would act as a major source for the torque on the superfluid, resulting in a relaxation even faster than in the absence of any pinning (Tsakadze & Tsakadze 1980; Adams, Cieplak & Glaberson 1985). In order to allow for the suggested *large* frequency difference between the superfluid and the crust, while maintaining a rotational lag (between the superfluid and its vortices) *smaller* than the associated critical value, one is forced to assume that the pinning is “switched off”, which would be in contradiction with the assumed pinning conditions. Nevertheless, the superfluid relaxation for such free (unpinned) vortices should still take place very quickly, as is further discussed below.

Thus, the upper limit on the frequency difference $\Delta\Omega$ between the crust and the superfluid (Ω_{sp}), at the beginning of the time period of interest τ_{sp} and *after* the “fast” early relaxation of the superfluid (discussed above), would be $\Delta\Omega = \omega_{\text{sp}} \sim 3.5 \times 10^{-6}$ rad s $^{-1}$; see the discussion in §4.1 below for a more detailed reasoning. This is the maximum permissible frequency difference that one might, in principle, consider to be further equilibrated between the crust and the superfluid. In contrast, a value of $\Delta\Omega = \Delta\Omega_c \sim 1.3 \times 10^{-4}$ rad s $^{-1}$ has been adopted in APC. The corresponding time scale τ_{sp} , for an assumed spin-up of the superfluid, may be estimated from (Basym et al. 1969) (see also Eq. 2b

in APC)

$$(\Delta\dot{\Omega}_c)_{\text{sp}} = \frac{I_{\text{sp}}}{I} \frac{\Delta\Omega}{\tau_{\text{sp}}} \quad (5)$$

where $(\Delta\dot{\Omega}_c)_{\text{sp}}$ is the magnitude of the change in $\dot{\Omega}_c$ due to the spinning up of the superfluid. Adopting the same parameter values as in APC, ie. $(\Delta\dot{\Omega}_c)_{\text{sp}}/\dot{\Omega}_c = 0.2$, $\frac{I_{\text{sp}}}{I} = 5.3 \times 10^{-3}$, $\Delta\Omega = \omega_{\text{sp}} = 3.5 \times 10^{-6} \text{ rad s}^{-1}$, and $\dot{\Omega}_c = 9.5 \times 10^{-11} \text{ rad s}^{-2}$ for Vela, Eq. 5 then sets an upper limit of

$$\tau_{\text{sp}} < 0.3 \text{ hr}, \quad (6)$$

which is *too short* in comparison with the observed timescales $\sim 0.4 \text{ d}$. Hence, the crust-superfluid cannot be the cause for the observed large spin-down rates even in the case of 1988 glitch of the Vela pulsar, addressed in APC. The disagreement between the predicted and observed timescales would be even worse for the case of 1991 glitch of the same pulsar, having observed values of $\Delta\dot{\Omega}_c/\dot{\Omega}_c \sim 60\%$ over a similar relaxation time (Flanagan 1995). Also, an attempt to apply the same crust-superfluid spin-up scenario to the case of PSR 0355+54 would result in more than *three* orders of magnitudes difference between the predicted τ_{sp} and the observed relaxation time $\sim 40 \text{ days}$.

4.1. Further reasoning for ω_{sp} , against $\Delta\Omega_c$

The above, rather obvious, conclusion (about the proper value of the frequency difference between the crust and the superfluid at the beginning of the long term relaxation) may be further explained by focussing attention on the behavior of the rotation frequency Ω_L of the *vortices*, in the region of interest identified by Ω_{sp} . Since this has not been explicitly specified in APC we, therefore, discuss the two exclusive possibilities that might, in principle, arise and which could be physically justified. Both cases lead, however, to the same conclusion; intermediate cases for which no justification exist should naturally fall in between (and there is no indication in APC for any special effect due to such cases). It may be noted that the cases to be considered should not be, however, paralleled to the classification of (strong, weak, super-weak) pinning regions, invoked in the literature on the vortex creep model. The latter is based on the relative magnitude of the critical lag and

reflects the long term behavior of the superfluid relaxation toward its steady state lag value. In contrast, the following two cases concern the instantaneous response of the originally pinned vortices upon a sudden jump in the rotation rate of the container (see Fig. 1). The vortices might be spun up along with the crust (container), and remain pinned *during* the sudden spin-up of the container (case **a**). Else, they could relax to a state of co-rotation with the local superfluid, assuming the pinning to be temporarily broken (**b**). Hence, the rotational frequency of the vortices in the region of interest would be such that either

$$\Omega_L = \Omega_c \quad (\text{pinning conditions}), \text{ or else } (7)$$

$$\Omega_L = \Omega_{\text{sp}} \quad (\text{Helmholtz theorem}), \quad (8)$$

just *at* the beginning of the interval τ_{sp} , namely after the jump in Ω_c (the observable glitch) has been accomplished (see Fig. 1a),

In the case (**a**), the superfluid (Ω_{sp}) must have also been spun up, along with the crust and the vortices, to (at least) a state such that $\Omega_{\text{sp}} - \Omega_c = -\omega_{\text{sp}}$ (contrast with the scenario adopted by APC as depicted in Fig. 1a). Otherwise the pinning would be broken (contrary to the assumption) by the associated radial Magnus force on the vortices. That is, if the superfluid rotation rate is assumed to retain its pre-glitch value, while the pinned vortices have been spun up along with the crust, the instantaneous (negative) lag between the superfluid and its vortices far exceeds its critical value. Under such conditions, the superfluid (spin-up) relaxation could not be impeded by the pinning forces. The relaxation would occur on short timescales similar to the case of free vortices, also according to the vortex creep model (see, eg., the discussion related to Eq. 11 in Alpar et al. 1984). Such a fast relaxation of the superfluid in the crust of a neutron star, when the lag exceeds its critical value, is in fact invoked in the vortex creep model as the cause of the glitches (Anderson & Itoh 1975; Alpar et al. 1984). Given the existing (two minute) upper limit on the rise time of the glitch (Flanagan 1995), the superfluid spin-up (for Ω_{sp} , in the present case, until its rotational lag with its vortices drops to values smaller than the critical value) has to be likewise accomplished on a time scale of a minute (contrast with τ_{sp}). Formally, this may be verified from the following relation which is prescribed, in the creep model,

for such cases when the value of the lag $\omega \gg \omega_{\text{crit}}$

$$v_r = v_0 \exp\left[-\frac{E_p}{kT} \left(\frac{\omega_{\text{crit}} - \omega}{\omega_{\text{crit}}}\right)\right] / \left\{ \exp\left[-\frac{E_p}{kT} \left(\frac{\omega_{\text{crit}} - \omega}{\omega_{\text{crit}}}\right)\right] \right\}$$

which amounts to

$$v_r \sim v_0, \quad (10)$$

where v_r is the vortex radial velocity, and $v_0 \sim 10^7$ cm/s corresponds to a spin-up (down) time scale ~ 0.1 s. Indeed, laboratory experiments on superfluid Helium have also showed (Tsakadze & Tsakadze 1975; Alpar 1987; Tsakadze & Tsakadze 1980) that a pinned superfluid either spins up *along* with its vessel, or it never does so during the subsequent spinning down of the vessel (for conditions corresponding to $|\Omega_{\text{sp}} - \Omega_{\text{L}}| < \omega_{\text{sp}}$).

The case **(b)**, on the other hand, is not in accord with the general pinning conditions assumed in the vortex creep model, and is not likely to be invoked in that context. Nevertheless, the superfluid spin-up in the crust of a neutron star, for such a case of free unpinned vortices, is again expected to occur over very short timescales. The longest timescale for the spin-up of the crust by freely moving vortices, due to nuclear scattering alone, has been estimated (Epstein et al. 1992) to be only $\lesssim 5$ s, for the Vela pulsar. It is only natural that the conclusions of the above two cases are the same, as the pinned vortices should behave like the free ones, once the critical lag is exceeded.

Therefore, and in either cases **(a or b)**, the superfluid would be spun up within a period of *only few seconds* to (at least) a frequency such that $\Omega_{\text{sp}} - \Omega_{\text{c}} = -\omega_{\text{sp}}$, while the observable jump in Ω_{c} takes place at the glitch (see Fig. 1b). It is noted that the steady-state lag ω_{sp} according to the vortex creep model, in the so-called non-linear regime, would be slightly smaller than the critical lag (though slightly larger in the absence of any creeping). The difference is however a tiny fraction of the critical lag (Alpar et al. 1984), and may therefore be neglected in the present discussion if a non-linear regime is assumed. In contrast, a “linear” regime is also invoked in the vortex creep model for which $\omega_{\text{sp}} \ll \omega_{\text{cr}}$. However, the above conclusion remains the same, even for this case, and a “rapid” superfluid spin-up is again expected until $|\omega| \lesssim \omega_{\text{sp}}$ is achieved! This is because, according to the creep model the spin-down

(up) rate depends “exponentially” on the difference $(\omega - \omega_{\text{sp}})$; see Eq. 28 in Alpar et al. (1984). Hence, (b) relaxation of the superfluid under the assumed conditions with $\omega_{\text{cr}} > |\omega| > \omega_{\text{sp}}$ should again take place on a time scale much shorter than the observed effect over τ_{sp} , even for the case of a linear regime.

5. Superfluid Spin-up

Moreover, the suggested spin-up scenario of APC should be dismissed at once since the required torque on the superfluid, during τ_{sp} , may not be realized at all, under the assumed conditions of (creeping of the) pinned vortices (see Fig. 1a). That is the pinned superfluid could not be spun *up* by the crust (ie. its container) while the latter is spinning *down*. This is simply because a spinning down vessel (or even one with a stationary constant rotation rate) albeit rotating faster than its contained superfluid could not result in any further *spin up* of the vortex lattice which is, by virtue of the assumed pinning, already *co-rotating* with it! As is well-known, an inward radial motion of the vortices, associated with a spin-up of the superfluid, requires the presence of a corresponding forward azimuthal external force acting on the vortices. This is indeed a trivial fact, considering that any torque on the bulk superfluid has to be applied primarily on the vortices. However, no *forward* azimuthal force (via scattering processes between the constituents particles of the vortex-cores and the crust) may be exerted by the spinning *down* crust on the vortex lattice which is already co-rotating with it. The azimuthal external force F_{ext} , being the viscous drag of the permeating electron (and phonon) gas co-rotating with the crust, depends on the relative azimuthal velocity v_{rel} between the *crust* and the *vortices*, as well as the associated velocity-relaxation timescale τ_v of the vortices. The external drag force, per unit length, is given as

$$n_v F_{\text{ext}} = \rho_c \frac{v_{\text{rel}}}{\tau_v}, \quad (11)$$

where n_v is the number density of the vortices per unit area, and ρ_c is the effective density of the “crust”. Hence, for a spin-up of the superfluid to be achieved, the crust may impart the corresponding torque on the vortices only if it (tends to) rotates faster than the vortices, so that v_{rel}

points to the proper forward direction. Accordingly, a superfluid spin-up requires the crust to be itself spinning up, or else if the crust is spinning down, the vortices must be already rotating slower than the crust; a requirement which is against the pinning condition. It should be trivially clear that the Magnus force could not be responsible for the required external torque, as it is an internal force exerted by the superfluid itself. Therefore, *no further superfluid spin-up* might be expected to occur during the interval τ_{sp} , namely after the initial fast spinning up of the crust, as well as the superfluid and its *vortices*, has been accomplished during the glitch rise time (compare Fig. 1a with Fig. 1b).

The suggested long-term (over time τ_{sp}) superfluid spin-up in APC is a generalization of the vortex creep model to the case of a *negative* lag, in contrast to the usual applications of the model to spin-downs driven by a positive lag. However, according to the existing formulation of the vortex creep model, a spinning up of the superfluid would require a *positive* accelerating torque N_{em} acting on the whole star (see, eg., Eqs. 28, and 38 in Alpar et al. 1984). Application of the same formalism (as is attempted in Eq. 5 of APC) to the suggested case of an spin-up in presence of the given *negative* N_{em} is not, a priori, justified; it is indeed contradictory.

The vortex creep model suggests that a radial Magnus force, due to a superfluid rotational lag, results in a radial bias in the otherwise randomly directed creeping of the vortices (Alpar et al. 1984; see Jahan-Miri 2005 for a critical discussion of the vortex creep model on this, and other, grounds). This might be, mistakenly, interpreted to imply that given a negative lag the inward creeping motion of the vortices, hence a superfluid spin-up, should necessarily follow, irrespective of the presence or absence of the needed torque on the superfluid. As already noted, the role of driving the vortices inward, ie. spinning up of the superfluid, may not be assigned to the Magnus force. The Magnus force associated with the rotational lag is a *radial* force and is also an internal force exerted by the superfluid *itself*; both properties disqualifying it from being the source of a torque on the superfluid. Accordingly, the point to be emphasized is that the obvious requirement for a spin-up process, namely the realization of the needed torque, is indeed missing in the sug-

gested mechanism of APC. Moreover, the inability of the superfluid to be spun up, in this case, is *not* a direct consequence of the fact that pinned vortices may not respond freely to an applied external torque. Rather, the vortices under the assumed conditions do not have any “tendency” for an inward radial motion, in spite of the presence of an inward radial Magnus force which is balanced by the pinning forces. Thus creeping motion of the vortices may not be invoked as a resolution; radial creep should be prohibited accordingly. A change in the spin frequency of a superfluid involves not only a radial motion of the vortices but also a corresponding azimuthal one, as may be also verified from the solution of equation of motion of vortices during a superfluid rotational relaxation (see Eq. 9 in Alpar & Sauls 1988, and Eq. 4 in Jahan-Miri 1998). The torque may be transmitted only during such an azimuthal motion and would nevertheless require and initiate a radial motion as well. Therefore, purely *radial* creeping of the vortices, which is implied by the existing formulation of the vortex creep model, may not be invoked as a spinning-up mechanism during the transition from $\Omega_{\text{sp}} - \Omega_{\text{L}} = -\omega_{\text{sp}}$ to $\Omega_{\text{sp}} \gtrsim \Omega_{\text{L}}$. That is to say, no radial (creeping) motion of the vortices is permitted, for the assumed case, because the spinning down crust could not impart any *forward* azimuthal force on the pinned vortices. The superfluid would rather remain decoupled at a constant value of Ω_{sp} (if not spinning down) during this transition which is achieved due only to the spinning down of the crust, as depicted in Fig. 1b.

6. Concluding

Decoupling of (a part of) the moment of inertia of the crust of a neutron star at a glitch, from the rest of the co-rotating star, could readily account for the excess post-glitch spin-down rates comparable to the fractional moment of inertia of the decoupled part. The same preliminary fact applies to a (partial) decoupling of a (pinned) superfluid component in the crust, or elsewhere in the star, as well. A decoupled component (say, in the crust) could, in principle, result in an even larger excess spin-down rate of the star if it is further assumed to be spinning up while the rest of the star is spinning down; ie. a *negative* coupling instead of a mere decoupling. Nevertheless, here we have shown that the only suggested mechanism for such

a *negative* coupling of a pinned superfluid part in the crust not only fails quantitatively to account for the observed effect in pulsars, it is also ruled out conceptually since the required torque on the superfluid could not be realized at all.

Given the standard picture of the interior of a neutron star (Sauls 1989; Pines & Alpar 1992), one is thus left to speculate on the possible role of the stellar core to induce the observed effect. That is, the observed large spin-down rates, over timescales of a day and more, should be caused by a decoupling of (a part of) the stellar core. The large moment of inertia I_{core} of the core, with $\frac{I_{\text{core}}}{I} \sim 90\%$, may easily account for the observations. Nevertheless, a non-superfluid component in the core would couple to the crust on very short timescales ($< 10^{-11}$ s) (Baym et al. 1969a), and could not have any footprint left in the observed post-glitch relaxation. Also, a core-superfluid with free (unpinned) vortices would be again expected to have very short coupling timescales of the order of less than one or two minutes (Alpar & Sauls 1988; Pines & Alpar 1992; Jahan-Miri 1998). However, the pinning of the superfluid vortices to the superconductor fluxoids in the core of neutron stars, might offer a way out of the dilemma. The effect has been originally suggested on theoretical grounds (Muslimov & Tsygan 1985; Sauls 1989; Jones 1991b), while its observable consequences for the rotational dynamics of a neutron star as well as its magnetic evolution have been investigated by various authors (Srinivasan 1990; Jones 1991b; Chau, Cheng & Ding 1992; Jahan-Miri 1996; Ruderman, Zhu & Chen 1998; Jahan-Miri 2000; 2002).

Very briefly, the peculiar feature of the assumed pinning in the core, that is the *moving* nature of the *pinning sites*, has to be highlighted, in this regard. The fluxoids are indeed predicted to undergo a steady outward radial motion throughout the active lifetime of a pulsar (Chau, Cheng & Ding 1992; Jahan-Miri 2000). At a glitch, a departure in the lag from its earlier critical value, causes a (dynamically partial) decoupling of the core, which may explain the observed initial large spin-down rates soon after a glitch (that could not be possibly caused by the crust, as discussed above). Nevertheless the core superfluid does spin down even before the critical lag value is restored, simply because the pinning barriers (the fluxoids),

hence the superfluid vortices pinned to them, are moving radially, at all times. Otherwise, for the core superfluid to remain completely decoupled (the vortices being stationary) the superfluid rotation lag should amount to its critical value! since a crossing-through of the vortices and fluxoids, ie. unpinning events, would be inevitable. For the core superfluid, a *decoupling* accompanies and implies *unpinning!*, contrary to the usual case of stationary pinning sites, as for the crust. Hence, during a post-glitch recovery phase (while the lag is still far from its critical value) the vortices move out along with the fluxoids, keeping the superfluid in a spinning down state, albeit at a slower rate than before the glitch. A quantitative modelling of the effects of a pinned superfluid component in the core on the post-glitch response, as well as its role in a (free) precession of the star, remains to be further studied in details.

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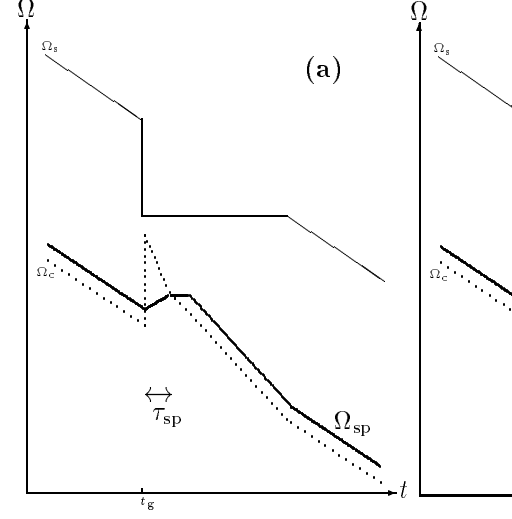


Fig. 1.— As is shown, schematically, by the *thin* and the *dotted* lines, a superfluid, as in the crust of a neutron star, whose vortices are pinned and co-rotating, at a rate Ω_c , with its spinning down vessel, may spin-down at the same rate as the vessel provided a certain lag between its rotation frequency Ω_s and Ω_c is maintained. A decrease in the lag, say at a glitch, results in a decoupling of the superfluid and hence a larger spin-down rate for the vessel. The superfluid starts spinning down again once the lag is increased to its steady-state value. The *thick* line represents the superimposed behavior of a second superfluid component, Ω_{sp} , which supports a much smaller steady-state lag. Its behavior as implied in APC90 is shown in the panel (a), in contrast to that suggested here, shown in (b). The unresolved rising time of Ω_c at the glitch instant $t = t_g$ should be reckoned as a measure of the expected coupling time of the superfluid due to free motion of vortices, in contrast to the suggested spin-up period τ_{sp} in (a).